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Influence of unbalanced operation time means and uneven buffer allocation on unreliable merging assembly line efficiency

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Unbalanced, unreliable (UR), unpaced, merging assembly lines are simulated in this study with varying line lengths, buffer storage capacities, imbalance degrees and unequal mean operation time configurations and uneven buffer capacity (BC) allocation. This paper contributes to the literature by suggesting that, in many cases, imbalance can improve merging lines' performance, as compared to a corresponding balanced merging line. It was found that an inverted bowl or descending patterns for mean operation times (MTs), and an inverted bowl (concentrating BC towards the centre of the line) or an ascending pattern for buffer allocation, result in higher throughput (TR). In terms of average buffer level (ABL), the best pattern is a monotone decreasing order regarding MTs and a monotone increasing order with respect to BC allocation. Additionally, it was found that when considering a profit function, the best performing patterns for UR lines tend to be the patterns that reduce ABL, even when considering very low inventory holding costs; contrary to the behaviour of the profit function in reliable lines, which suggests that either patterns that increase TR or reduce ABL can lead to a good performance, depending on the values of the unitary inventory holding costs.

Keywords: unreliable; unbalanced merging lines; service time means; throughput; average buffer level; simulation; bowl phenomenon

1. Introduction

Unpaced, parallel merging lines are viewed as high-volume probabilistic serial waiting lines. Work-in-process (WIP) inventories are commonly kept between stations so that partially completed items are moved to a buffer storage location.

In developing economies, remanufacturing and reverse logistics, unpaced assembly lines are common. Given the explosive growth in remanufacturing and related processes and with sizeable production occurring in developing economies, this highlights the global implications of research on assembly lines across industries and stresses the contribution of this study.

In addition, queueing networks featuring parallel merging stations are natural models for a variety of computer and manufacturing systems, including parallel computer networks, supply chains and material control strategies (Hudson, McNamara, and Shaaban 2015).

When designing a merging assembly line, the allocation of operators working at different speeds and the allocation of total available buffer capacity (BC) along the line become an important consideration for average buffer level (ABL) and throughput (TR) performance.

Research in this area has predominantly focused on how best to achieve a 'balanced' line (Battaïa and Dolgui 2013; Bentaha, Dolgui, and Battaïa 2015), where the operator's mean service time (MT) at each workstation is the same, as this design type has been perceived as ensuring high efficiency and resource utilisation, predictable output and minimal waste.

In real life, however, processing times have been shown to be non-identical at different workstations, even in automated lines (Tempelmeier 2003). In manual, unpaced lines, the operators at each station can work at different MTs for several reasons: they can vary their speed according to their motivation level, physical capacity, task complexity or due to an uneven work allocation along the line. Furthermore, previous studies have shown that the best design for single serial lines in terms of throughput rate is to arrange mean operation times (MTs) in a 'bowl' shape (McNamara, Shaaban, and Hudson 2016; Hillier and Boling 1966) and to allocate BC as evenly as possible (McNamara, Shaaban, and Hudson

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2013; Lambrecht and Segaert 1990); whereas studies on merging lines (McNamara et al. 2018; Shaaban, McNamara, and Dmitriev 2017) have suggested that a bowl pattern for MT and a balanced pattern for BC are not the best for merging lines.

In addition, some research (see for instance Conway et al. 1988) indicated that buffer sizes are unlikely to be evenly distributed, as technical considerations often restrict the amount of space available in the line, thereby making it difficult to allocate total BC evenly amongst individual buffers.

An additional issue worth considering is the fact that production lines are likely to face another source of fluctuation, caused by downtime due to machine failure, with all the accompanying adverse impacts on performance. This paper, therefore, aims to investigate the issues of MT and BC imbalances when considering unreliability in merging lines, and to compare the behaviour of reliable and unreliable (UR) merging lines in the presence of such unbalanced patterns.

The remainder of this paper is structured as follows. A literature review is followed by a presentation of the research questions, motivation and study objectives. Subsequent sections discuss the methodology and design details and describe the study results and analyses. The paper ends with a summary, discussion, conclusions and future research directions.

2. Literature review

Hillier and Boling (1966) found that placing workstations with higher MTs at both ends of a single serial line can lead to a better TR performance, as compared to a balanced line counterpart. They termed this effect as the ‘bowl phenomenon’. Since then, the phenomenon was repeatedly retested, with varying degrees of support (McNamara, Shaaban, and Hudson 2016). More recent studies on single serial lines have shifted to imbalance patterns, rather than just the bowl phenomenon (see Das et al. 2010; McNamara, Shaaban, and Hudson 2013; Shaaban, McNamara, and Hudson 2015; Hudson, McNamara, and Shaaban 2015; Hillier 2013; Shaaban and Hudson 2009).

On the topic of two or more assembly lines with shared resources, most studies have focused online balancing under the following different names:

- Two-sided assembly lines (see, for example, Chiang, Urban, and Luo 2016; Purnomo, Wee, and Rau 2013; Gansterer and Hartl 2018).
- U-shaped (see, e.g. Ağpak, Fatih Yegül, and Gökçen 2012; Rabbani, Moghaddam, and Manavizadeh 2012; Delice, Kızılkaya Aydoğan, and Özcan 2016).
- Parallel (e.g. Akpınar and Mirac Bayhan 2011; Kucukkoc and Zhang 2014; Tiacci 2015).
- Fork/join queue networks (e.g. Barron 2015; Sönmez, Scheller-Wolf, and Secomandi 2017).
- Merge/split (e.g. Liu and Li 2009; Liu and Li 2010).

For a literature review of line balancing methods, see Battaïa and Dolgui (2013) and Sivasankaran and Shahabudeen (2014).

On the other hand, a few studies discussed two or more assembly lines with unequal MTs and BCs. They can generally be classified into two broad groups: reliable and UR. Below is a review of the relevant works.

2.1. *Reliable lines*

Baker, Powell, and Pyke (1993) analysed a three-station merging system with two feeder stations and one assembly station. They found that the optimal configuration was unbalanced and that TR remained steady for an assembly station work allocation ranging from 0.42 to 1. Their simulations of longer 2-station feeder lines showed smaller improvements in TR overall, and that TR results were better in unbalanced than in balanced systems. In 1995, Baker and Powell developed an efficient approximation method for determining the output of a simple three-station assembly system with random unbalanced processing times.

Magazine and Stecke (1996) found support for the notion that an unbalanced merging line can perform equally well, or better, than a corresponding balanced system. Their goal was to determine where to allocate capacity in 2 or 3 station lines, split into parallel servers, in order to maximise TR. They suggested that for fixed resources, the ‘symmetrical allocation’ property holds, i.e. having equal numbers of parallel servers on stations one and three, with more assigned to the middle station. When imbalance becomes too severe, a server is removed from the middle station and one is added to the first and third stations to keep TR optimal. They also noted that for any set of parameters maximising TR, the ‘bowl phenomenon’ holds true.

Futamura (2000) studied optimal allocation of servers to serial queueing networks with unbalanced MTs, coefficients of variation and BCs, which showed a general interaction between the CV of the service time distribution and stations’ number of servers.

Leung and Lai (2005) considered the assignment of parallel workstations to improve cycle times when compared to simple assembly systems. They concluded that off-line parallel systems resulted in a reduction of buffer requirements and a reduced sensitivity to imbalance in terms of MT and CV, compared to online and tunnel-gated systems.

Abu Qudeiri et al. (2008) used a genetic algorithm to find the optimal design for serial-parallel production lines with uneven buffers and stations containing varied machine numbers and types. They found that applying the algorithm to a parallel line system with five machines in each line, resulted in a production efficiency increase from 80% to 85%.

Recently, the performance of unbalanced, reliable and unpaced merging lines was assessed by Shaaban, McNamara, and Dmitriev (2017) and by McNamara et al. (2018) under various simulated configurations. The improved performance was obtained for an MT balanced line arrangement and a monotone decreasing order of operation times, with the former generally resulting in a lower TR and the latter leading to a lower ABL than that of a corresponding balanced line. Moreover, they suggested that higher TR and lower ABL can be attained by a balanced allocation of BC as well as by a BC allocation towards the end of the line.

Therefore, previous research suggested that while the MT bowl pattern for simple serial lines is the best in terms of TR, other MT configurations can perform better for merging lines. In addition, research on BC patterns in single lines indicated that a balanced pattern works best for TR, but in a merging line, an ascending order pattern might result in a good TR performance.

2.2. *UR lines*

In an early simulation study, Moberly and Wyman (1973) compared a system with two serial lines operating in parallel with a production line comprised of an equal number of stages, where each stage had two stations that merged. Both systems were subject to failure and had normally distributed processing times. They found that a configuration of a series of merging stations provided better performance than a series of parallel serial lines.

Liu and Buzacott (1990) developed a method to predict the performance of assembly systems using an assembly stage that is fed by two or more stages which have unequal cycle times and are subject to failure.

Gershwin (1991) analysed a class of assembly/disassembly network systems in which machines are UR, buffers are finite, and machines perform operations whenever none of their upstream buffers are empty and none of their downstream buffers are full, and the network structure is a tree. An approximate decomposition method to estimate TR was presented.

Focusing on three-station assembly systems, Bhatnagar and Chandra (1994) used simulation to study the effect of variability due to UR stations and imperfect yields on these systems. Greater TR improvements were found from increasing the production rate (lowering the MTs) of individual stations than from increasing BC.

Jeong and Kim (1999) presented an approximation method to evaluate the performance of tree-structured assembly/disassembly systems in which each station consists of multiple identical machines. It was assumed that the failure, repair and processing times were exponentially distributed and that BCs were finite. Jeong and Kim (2000) also investigated buffered production systems, with feeder stations merging into an assembly station. They developed heuristics to determine the line configuration which would bring about a desired TR at a minimal cost. Like their previous paper, they assumed finite BCs and exponential times for failure, repair and processing times.

Tan (2001) studied an UR merging system comprised of two stations in parallel with different processing rates that feed into a common buffer, which in turn feeds an assembly station. He developed a decomposition method for determining TR and ABL.

Patchong and Willaeys (2001) developed a methodology for serial-parallel flow lines, which estimates equivalent parameters of sets of parallel machines. They showed that their method can successfully be applied to lines with differing processing times and unreliability conditions for the diagnosis of TR and ABL performance.

Yuan and Liu (2005) studied an UR assembly system in which different types of components are processed by two separate work centres before merging to an assembly station with random breakdowns. They obtained formulas for system state probabilities, blocking, starvation, stockout and system availability in the steady state. They also obtained the distributions of blocking and first failure times.

Alexandros and Chrissoleon (2009) examined a model of a serial flow line with two workstations and an intermediate buffer, using an exact Markovian analysis. Each workstation consists of multiple UR parallel machines. The processing, failure and repair times of the parallel machines at each workstation were assumed to be exponentially distributed with non-identical mean rates.

Utilising interdisciplinary approaches to improve assembly systems with constant processing times but random failure rates, Bulgak (2006) used a genetic algorithm and simulation to yield maximum output, while optimising the buffers in merging and split unpaced assembly systems. He found that the optimal buffer allocation for 7- and 11-station lines was an unbalanced allocation when considering a merging line with unbalanced reliability along the line.

Recently, Jia et al. (2016) studied the transient behaviour of assembly systems with merging serial lines, comprised of Bernoulli machines (subject to failure) with finite buffers. Formulas were derived to efficiently measure TR, WIP levels and probability that any station will be blocked or starved. They developed an analytical method for dealing with larger and more complex assembly systems with multiple feeder lines and merge stations.

Thus, whereas previous research into UR merging lines has focused on developing approximation methods for estimating TR and ABL, to the best of our knowledge no study has specifically investigated the comparative performance of different MT and BC imbalance patterns in UR stochastic merging lines.

From the above review, it is clear that merging line research has mainly focused on the development of mathematical and line balancing models. To contribute here to a better understanding of the behaviour of unbalanced, UR merging lines and to get support in developing intuition about these production systems (Gershwin 2018), simulation and statistical analyses were undertaken to investigate whether MT and BC imbalance can yield better TR and ABL results than a balanced pattern as well as to better understand how different design factors impact merging line efficiency. Additionally, the current study compares the performance of an *UR* merging line to an equivalent *reliable* merging line.

3. Motivation, objectives and research questions

In this paper, UR, MT and BC unbalanced merging assembly lines were investigated. Since there is a paucity of research on the behaviour of merging lines, this study contributes to the literature through a systematic investigation and fills some of the gaps left by previous research. Its main objective is to assess the performance of such lines for various patterns of MT and BC imbalance in order to provide important guidance for their design. The research questions are:

(1) What is the influence of the patterns of MT and BC imbalance on the performance of the simulated merging line performance as compared to that of an equivalent balanced line?
(2) Which of the patterns lead to the best line throughput and average buffer level performance?
(3) What are the relative contributions of MT imbalance pattern, imbalance degree, BC allocation pattern, line length and buffer capacity to line performance?
(4) Which pattern is the best in terms of combined TR and ABL performance?
(5) What is the effect of unreliability on the performance of unbalanced MT and BC merging lines?

To our knowledge, no previous studies have explicitly addressed these issues.

4. Methodology and experimental design

Merging line systems are difficult to evaluate because of their large state spaces; therefore, they cannot be decomposed exactly. An exact solution for a Markovian merging line network can only be obtained by analysing the underlying Markov chain using numerical methods. Exact solutions are not computationally feasible for lines longer than three stations and for non-exponential distributions, and so in many cases, authors use simulation to study the workload allocation problem under more general conditions.

Due to the limitations of mathematical approaches in representing the more complex merging lines typically reported with positively skewed operation times, computer simulation was viewed as the most suitable tool for this study. The UR, unbalanced merging line was studied using the Simio 9.147 simulation software (Kelton, Smith, and Sturrock 2014).

4.1 *Study design*

As one of the questions of this study is concerned with studying the effect of unreliability on merging lines, the same full factorial experimental design from previously published reliable lines' results was used. A full factorial experimental design considers all desired levels of a given factor combined with all levels of every other factor. In a full factorial design, the effect of independent variables on dependent variables can be measured and it is possible to investigate individual as well as combined variable effects. In addition, more sensitive statistical tests can be used.

The experimental design and results of McNamara et al. (2018) were used as a basis for the current paper to study the effects of MT patterns on UR merging lines, while the study of Shaaban, McNamara, and Dmitriev (2017) was used as a basis for studying the effect of BC patterns.

So, the current study considers two separate independent sets of experiments, as a combination of both factorial sets (MT and BC) will be too burdensome. The first set deals with MT imbalance patterns (MTP) and considers a balanced BC allocation, whereas the second set considers the BC allocation patterns (BCP) with a balanced MT pattern.

Aligning with Slack's (1982) suggestion that the unpaced service times found in practice are more closely described by a right-shifted Weibull probability distribution, more realistic processing times were simulated using the three-parameter Weibull distribution (Law 2014) with a shape parameter of $k = 1.6$ and a coefficient of variation equal to 0.27. The scale (λ) and location (α) parameters varied, depending on the MT imbalance degree (DI) and pattern. Overall, the average operating time for each parallel line was equal to 10 minutes. The full set of experimental values for the Weibull distributions per station can be found in the Appendix.

For the specific merging line studied, the independent variables studied were:

- Line length (number of stations), *N*.
- Capacity of each buffer, BC
- Degree of imbalanced service time means, DI (the percentage difference in MT between the maximum or the minimum MT and the average MT).
- MT imbalance pattern, MTP (for parallel lines 1 and 2).
- Buffer allocation pattern, BCP (for parallel lines 1 and 2).

4.2 *Performance measures and statistical tools*

In this paper, line throughput/output rate (TR) and ABL were utilised as dependent performance measures for the line. TR is most often used in line design by engineers and managers and is particularly valuable in high volume industries.

ABL is cost-related, and should be considered in operating environments with high overheads, and where space or the value of the raw material is at a premium. In such environments, one unit of BC can represent an investment of several thousand U.S. dollars (Tempelmeier 2003). This measure is more valuable in industries where the goal is lean buffering, with a focus on perishable goods and a need of low in-process stocks.

Moreover, to assess the joint effects of MT and BC patterns on TR and ABL, the following profit function was considered, based on Hillier (2013):

$$rTR - cABL \tag{1}$$

where r is the unitary revenue generated by TR and c is the average holding cost of inventory per unit per time period.

Dividing Equation (1) by r, the profit function can be studied by the overall relationship between c and r, i.e. $h = c/r$, as follows:

$$Profit = TR - hABL \tag{2}$$

Therefore, Equation (2) will be used to assess the impact of different MTPs and BCPs on the joint effects of TR and ABL.

This study seeks to determine conditions which increase TR and/or reduce ABL. The following statistical techniques were used to analyse the TR and ABL data:

- Dunnett's *t*-test was used to compare the performance of unbalanced MTP and BTP to the balanced pattern counterpart.
- Multiple pairwise comparisons (Tukey's HSD) were carried out to compare the relative performance of MT and BC patterns with varying factor levels.
- Generalised Linear Model (GLM) analysis was used to identify the relative contributions of the independent variables to the dependent performance variable.

The 'R' statistical package (The R Foundation 2016), version 3.4.0 was employed to analyse TR and ABL data.

4.3 *Simulation parameters and model assumptions*

An appropriate warm-up period for the simulation run is needed to ensure that observations are as close to normal operating conditions as possible. Law (2014) proposed running a preliminary simulation of the system, selecting one output variable for observation.

A trial procedure using Welch's methodology (Welch 1983) has established that after an initial run of 20,000 minutes, acceptable steady-state behaviour was found. All data collected during the first 20,000 minutes were discarded and 300 independent production runs of 100,000 minutes each were carried out in order to produce a confidence interval size of less than

1% of the mean TR. Additionally, the same random number seed was used in all experimental settings to generate an identical event sequence for all designs and to highlight any configuration contrasts.
Several customary line type assumptions were made, including:

- Only one type of product flows in the system, with no changeovers and no defective parts being produced.
- Set up time (to move work units in/out of the storage buffers) is considered negligible.
- The first station is never starved and the last station is never blocked.

The above operating conditions are in agreement with previous simulation studies (e.g. El-Rayah 1979; Powell 1994; Sabuncuoglu, Erel, and Gocgun 2006).

Figure 1 shows the merging line system under consideration in this study, where S_{ij} is the station i in parallel line j, B_{ij} is buffer i in parallel line j, and F_j is the buffer feeding the Merging Station in parallel line j.

4.4 *Failure and repair parameters*

Manufacturing equipment on the factory floor is typically UR. In UR merging lines, the stations are subject to random mechanical failure and repair events. An empirical study by Inman (1999) found that an exponential probability distribution with regard to both the mean time between failure (MTBF) and mean time to repair (MTTR) are representative of what is observed on actual manufacturing systems.

The failure rate used for this investigation was 0.001 breakdowns per minute, with the repair rate being 0.010 repairs per minute, i.e. MTBF was 1000 minutes and MTTR was 100 minutes. Consequently, line efficiency was determined to be 91% [MTBF 1000/(MTBF 1000 + MTTR 100)] – the same efficiency rate used by Altiok and Stidham (1983) and Hopp and Simon (1993). Times to failure and repair times were modelled as an exponential distribution, according to the findings of Inman (1999).

4.5 *Unique merging line design features*

As mentioned earlier, the experimental design features of this study are based on previous studies (Shaaban, McNamara, and Dmitriev 2017; McNamara et al. 2018) to be able to perform direct comparisons between reliable and UR lines. For both merging lines 1 and 2, line lengths of $N = 5$ and $N = 8$, (odd and even numbers) were studied, with evenly allocated buffer capacities of BC = 1, 2 and 4 units for MTP experiments, while BC = 2 and 6 were considered for BCP experiments.

Three levels of MT imbalance degrees were considered (DI% = 2, 5 and 12). Vonderembse and White (2003) argued that even well-balanced lines have idle times in the order of 2%. Hutchinson, Villalobos, and Beruvides (1997) indicated that a DI of 5% was considered acceptable. The DI value of 12% was used to ascertain the effect of a relatively large degree of imbalance.

Additionally, a 10-minute MT base case was used. For example, for $N = 5$, if the pattern is a monotone increasing order (/) and DI% = 5, the MTs at the five stations would be: 9.47 minutes, 9.73, 10.00, 10.26 and 10.53 minutes at stations 1–5, respectively. The MT values utilised are similar to those used by Blackstone and Cox (2002).

Five different MTPs were considered for each of parallel lines 1 (L1) and 2 (L2):

- A monotone decreasing order (\) – going from slowest to fastest operators
- A monotone increasing order (/) – going from fastest to slowest operators
- An inverted bowl arrangement (Λ) – the slowest operators placed in the middle
- A bowl arrangement (V) – the fastest operators positioned in the middle
- A balanced line arrangement (–)

In addition, five different uneven BCP for L1 and L2 were considered:

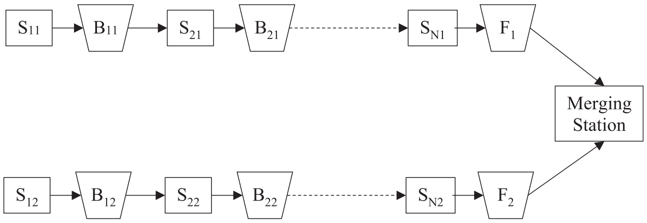

Figure 1. Merging line with N stations per each parallel line.

- A descending order (\) – concentrate available BC towards the line's start
- An ascending order (/) – concentrate available BC towards the line's end
- An inverted bowl shape (Λ) – concentrate available BC towards line's centre
- General – no concentration of available BC at one area of the line but unbalanced assignment (patterns G1 and G2)
- A balanced line arrangement (–)

Table 1 shows the complete set of experimental factors and the values considered per each factor. Overall, the number of simulation runs carried out was: 2 line lengths * 3 BC levels * 3 DI levels * 24 MTP + 6 for the balanced line (–, –) + 2 line lengths * 2 BC levels * 36 BCP = 586. The full set of experimental parameters can be found in the Appendix.

5. Simulation results and data analysis

TR and ABL data are presented in Tables 2–5.

> Research Question 1: What is the influence of the pattern of MT and BC imbalance on the performance of the simulated merging line performance as compared to that of an equivalent balanced line?

Multiple comparisons with control using the Dunnett's *t*-test were performed to gauge the influence of MTP on the TR and ABL data. The Dunnett's test revealed that none of the unbalanced MT patterns performing better than the balanced pattern (especially at DI% = 2, 5 and $N = 5$, BC = 1) have a statistically significant difference with the balanced pattern.

It can also be noted that at lower MT imbalance degrees (DI% = 2 and 5), the balanced line pattern is not significantly superior to the unbalanced patterns. However, at DI% = 12 the unbalanced patterns largely perform much worse than the balanced control (Table 2). In contrast, ABL results indicate that the MT descending order (i.e. the '\' pattern for L1 and the '\' pattern for L2: (\, \)) consistently outperforms the balanced line (Table 3).

In addition, results show that whenever a descending order was used in either parallel lines, very highly significant improvements over the balanced line ABL performance for the vast majority of the factor levels explored were found, whereas the ascending order pattern (/, /) performs very highly significantly worse than the control across the board.

When considering the influence of BCP, it was found that the balanced pattern (–, –) regularly outperforms the other patterns in terms of TR for $N = 8$ (Table 4), particularly for the descending order pattern (\, \), as highly statistically significant differences in TR were found between the balanced pattern and configurations with a descending pattern used in either parallel lines.

However, when $N = 5$, an inverted bowl BCP (Λ, Λ) has a higher TR with statistically significant differences than the balanced pattern. Furthermore, when $N = 5$ and BC = 2, two configurations with an ascending order BCP, i.e. (/, Λ) and (/, /), also have higher, statistically significant TR performance than the balanced pattern.

As for ABL, an ascending BCP in either parallel lines result in statistically significant better (lower) overall ABL values (Table 5), whereas the use of a descending BCP in either parallel lines result in statistically significant worse (higher) ABL values.

> Research Question 2: Which of the patterns lead to the best line throughput and average buffer level performance?

Table 1. Experimental factors and values.

Imbalance pattern	Line length (N)	BC per station	Percentage degree of imbalance in operation times (DI)	L1 Pattern	L2 Pattern
MTP	5, 8 stations	1, 2, 4 units	2, 5, 12%	(\)	(\)
				(/)	(/)
				(Λ)	(Λ)
				(V)	(V)
				(–)	(–)
BCP	5, 8 stations	2, 6 units	NA	(\)	(\)
				(/)	(/)
				(Λ)	(Λ)
				G1	G1
				G2	G2
				(–)	(–)

Table 2. TR data for an UR MT merging line with $N = 5$ and 8 parallel stations, BC = 1, 2 and 4 units, degree of imbalance (% DI) = 2, 5 and 12, various MTP, and a balanced line; $.p < .10$, $*p < .05$, $**p < .01$, $***p < .001$.

	Pattern		BC = 1			BC = 2			BC = 4		
	L1	L2	DI = 2	DI = 5	DI = 12	DI = 2	DI = 5	DI = 12	DI = 2	DI = 5	DI = 12
$N = 5$	–	–	0.517	0.517	0.517	0.559	0.559	0.559	0.617	0.617	0.617
	–	/	0.516	0.514	0.508***	0.559	0.558	0.550***	0.617	0.615	0.606***
	–	\	0.517	0.516	0.516	0.559	0.560	0.558	0.619	0.616	0.614
	–	V	0.516	0.516	0.513*	0.560	0.558	0.555.	0.617	0.616	0.613*
	–	Λ	0.518	0.516	0.518	0.560	0.560	0.559	0.618	0.617	0.618
	/	–	0.516	0.515	0.509***	0.558	0.557	0.549***	0.616	0.613*	0.605***
	/	/	0.516	0.511***	0.500***	0.557	0.554**	0.540***	0.615	0.611***	0.597***
	/	\	0.517	0.516	0.507***	0.558	0.558	0.547***	0.617	0.613*	0.603***
	/	V	0.517	0.512**	0.504***	0.558	0.556	0.545***	0.616	0.614.	0.600***
	/	Λ	0.516	0.514	0.508***	0.560	0.557	0.550***	0.616	0.615	0.604***
	\	–	0.517	0.517	0.516	0.560	0.562	0.559	0.618	0.618	0.615
	\	/	0.516	0.515	0.508***	0.558	0.557	0.549***	0.618	0.615	0.605***
	\	\	0.519	0.518	0.515	0.559	0.562	0.557	0.619	0.618	0.613**
	\	V	0.518	0.517	0.512***	0.561	0.558	0.555.	0.616	0.617	0.610***
	\	Λ	0.518	0.518	0.516	0.560	0.561	0.559	0.619	0.620	0.616
	V	–	0.516	0.515	0.513**	0.558	0.557	0.555.	0.615	0.615	0.612***
	V	/	0.515	0.515	0.506***	0.558	0.556	0.546***	0.615	0.613*	0.602***
	V	\	0.518	0.516	0.512***	0.560	0.559	0.554**	0.618	0.615	0.609***
	V	V	0.516	0.515	0.510***	0.558	0.557	0.553***	0.616	0.615	0.608***
	V	Λ	0.517	0.515	0.513*	0.559	0.558	0.556	0.616	0.618	0.611***
	Λ	–	0.517	0.518	0.517	0.560	0.559	0.560	0.618	0.617	0.617
	Λ	/	0.516	0.515	0.509***	0.559	0.558	0.550***	0.617	0.615	0.605***
	Λ	\	0.517	0.518	0.516	0.560	0.560	0.557	0.618	0.619	0.615
	Λ	V	0.516	0.517	0.514	0.560	0.560	0.557	0.617	0.617	0.613**
	Λ	Λ	0.518	0.518	0.518	0.560	0.560	0.560	0.618	0.618	0.617
$N = 8$	–	–	0.458	0.458	0.458	0.510	0.510	0.510	0.577	0.577	0.577
	–	/	0.457	0.456	0.451***	0.507	0.507	0.502***	0.576	0.576	0.569***
	–	\	0.459	0.458	0.458	0.508	0.509	0.509	0.577	0.578	0.579
	–	V	0.458	0.458	0.457	0.509	0.508	0.506*	0.576	0.576	0.575
	–	Λ	0.457	0.457	0.456	0.508	0.508	0.505***	0.575	0.576	0.573*
	/	–	0.457	0.457	0.451***	0.509	0.507	0.501***	0.576	0.574	0.566***
	/	/	0.457	0.454***	0.446***	0.507.	0.503***	0.495***	0.576	0.573*	0.559***
	/	\	0.458	0.457	0.451***	0.508	0.508	0.501***	0.576	0.574	0.568***
	/	V	0.458	0.455	0.449***	0.506*	0.506*	0.500***	0.576	0.572***	0.564***
	/	Λ	0.457	0.454**	0.449***	0.508	0.504***	0.497***	0.576	0.573*	0.563***
	\	–	0.460	0.459	0.459	0.510	0.511	0.509	0.578	0.577	0.576
	\	/	0.457	0.458	0.452***	0.509	0.506*	0.503***	0.576	0.576	0.569***
	\	\	0.459	0.460	0.460	0.509	0.511	0.511	0.579	0.579	0.578
	\	V	0.458	0.458	0.457	0.508	0.509	0.507	0.579	0.578	0.575
	\	Λ	0.458	0.458	0.457	0.509	0.509	0.505***	0.577	0.578	0.575
	V	–	0.457	0.457	0.456	0.508	0.506.	0.506**	0.577	0.577	0.574
	V	/	0.457	0.455.	0.449***	0.508	0.505***	0.499***	0.576	0.574	0.565***
	V	\	0.458	0.458	0.456	0.508	0.508	0.507.	0.576	0.577	0.574
	V	V	0.457	0.457	0.454***	0.507	0.507	0.504***	0.577	0.575	0.572**
	V	Λ	0.458	0.457	0.453***	0.507	0.507	0.504***	0.577	0.574	0.571***
	Λ	–	0.458	0.457	0.454**	0.506*	0.508	0.505***	0.577	0.576	0.573*
	Λ	/	0.457	0.455	0.449***	0.508	0.505***	0.498***	0.576	0.572**	0.565***
	Λ	\	0.458	0.459	0.455	0.509	0.509	0.506*	0.578	0.577	0.573*
	Λ	V	0.458	0.455*	0.454***	0.508	0.507	0.503***	0.577	0.574	0.570***
	Λ	Λ	0.457	0.456	0.451***	0.508	0.506**	0.502***	0.575	0.574	0.568***

Tukey's HSD multiple pairwise comparisons were used to rank the MT and BC imbalance patterns for overall performance across all values of N, BC and DI.

The results support the subjective reading of Tables 2–5 above using Dunnett's *t*-test. Table 6 shows a general results summary.

Table 3. ABL data for an UR MT merging line with $N = 5$ and 8 parallel stations, BC = 1, 2 and 4 units, degree of imbalance (% DI) = 2, 5 and 12, various MTP, and a balanced line; .$p < .10$, *$p < .05$, **$p < .01$, ***$p < .001$.

	Pattern		BC = 1			BC = 2			BC = 4		
	L1	L2	DI = 2	DI = 5	DI = 12	DI = 2	DI = 5	DI = 12	DI = 2	DI = 5	DI = 12
$N = 5$	–	–	0.662	0.662	0.662	1.313	1.313	1.313	2.575	2.575	2.575
	–	/	0.669***	0.679***	0.703***	1.327***	1.345***	1.396***	2.598***	2.642***	2.753***
	–	\	0.656***	0.647***	0.621***	1.302***	1.278***	1.224***	2.546***	2.500***	2.376***
	–	V	0.663	0.662	0.663	1.313	1.314	1.312	2.577	2.570	2.568
	–	Λ	0.663	0.663	0.661	1.313	1.314	1.312	2.577	2.578	2.570
	/	–	0.669***	0.681***	0.708***	1.326***	1.350***	1.405***	2.608***	2.653***	2.768***
	/	/	0.675***	0.694***	0.732***	1.341***	1.379***	1.458***	2.631***	2.712***	2.887***
	/	\	0.664	0.665***	0.671***	1.315	1.318*	1.327***	2.571	2.584	2.591**
	/	V	0.669***	0.680***	0.704***	1.327***	1.348***	1.396***	2.597***	2.645***	2.749***
	/	Λ	0.670***	0.682***	0.708***	1.326***	1.351***	1.402***	2.604***	2.652***	2.770***
	\	–	0.656***	0.643***	0.617***	1.299***	1.275***	1.219***	2.544***	2.494***	2.372***
	\	/	0.662	0.661	0.664	1.313	1.311	1.313	2.575	2.569	2.566
	\	\	0.649***	0.627***	0.574***	1.287***	1.242***	1.129***	2.512***	2.418***	2.171***
	\	V	0.656***	0.645***	0.621***	1.298***	1.280***	1.223***	2.544***	2.495***	2.375***
	\	Λ	0.656***	0.643***	0.616***	1.300***	1.278***	1.216***	2.536***	2.492***	2.362***
	V	–	0.664	0.664	0.666***	1.314	1.315	1.318*	2.580	2.572	2.577
	V	/	0.668***	0.679***	0.701***	1.326***	1.346***	1.388***	2.602***	2.636***	2.736***
	V	\	0.656***	0.648***	0.625***	1.301***	1.282***	1.234***	2.545***	2.504***	2.394***
	V	V	0.663	0.664	0.664	1.312	1.314	1.312	2.571	2.574	2.563.
	V	Λ	0.663	0.664	0.664	1.314	1.314	1.317	2.571	2.575	2.576
	Λ	–	0.661	0.661	0.659***	1.312	1.313	1.309	2.569	2.567	2.574
	Λ	/	0.668***	0.678***	0.702***	1.326***	1.347***	1.392***	2.602***	2.644***	2.745***
	Λ	\	0.656***	0.645***	0.617***	1.299***	1.277***	1.218***	2.544***	2.496***	2.366***
	Λ	V	0.662	0.662	0.660*	1.313	1.312	1.307*	2.571	2.573	2.563.
	Λ	Λ	0.662	0.662	0.658***	1.315	1.311	1.306***	2.573	2.573	2.562*
$N = 8$	–	–	0.674	0.674	0.674	1.323	1.323	1.323	2.583	2.583	2.583
	–	/	0.680***	0.687***	0.707***	1.336***	1.353***	1.393***	2.601**	2.639***	2.728***
	–	\	0.670***	0.662***	0.641***	1.317*	1.297***	1.254***	2.557***	2.517***	2.411***
	–	V	0.674	0.674	0.674	1.326	1.325	1.326	2.580	2.576	2.572
	–	Λ	0.673	0.674	0.671***	1.326	1.325	1.320	2.571	2.573	2.570
	/	–	0.679***	0.688***	0.709***	1.336***	1.354***	1.398***	2.603***	2.642***	2.745***
	/	/	0.684***	0.700***	0.733***	1.346***	1.379***	1.451***	2.620***	2.701***	2.863***
	/	\	0.676	0.675	0.680***	1.326	1.328	1.336***	2.580	2.589	2.604***
	/	V	0.679***	0.688***	0.708***	1.336***	1.354***	1.394***	2.601**	2.647***	2.737***
	/	Λ	0.679***	0.687***	0.706***	1.334***	1.353***	1.392***	2.596.	2.643***	2.728***
	\	–	0.669***	0.660***	0.639***	1.315***	1.297***	1.252***	2.546***	2.517***	2.416***
	\	/	0.674	0.674	0.676	1.326	1.326	1.328	2.581	2.577	2.582
	\	\	0.664***	0.647***	0.604***	1.303***	1.267***	1.179***	2.526***	2.449***	2.239***
	\	V	0.669***	0.660***	0.641***	1.315**	1.297***	1.255***	2.555***	2.514***	2.415***
	\	Λ	0.669***	0.660***	0.637***	1.313***	1.295***	1.247***	2.551***	2.507***	2.399***
	V	–	0.675	0.676	0.677*	1.324	1.327	1.328	2.583	2.580	2.580
	V	/	0.679***	0.688***	0.706***	1.333***	1.356***	1.390***	2.602***	2.639***	2.728***
	V	\	0.669***	0.662***	0.645***	1.315***	1.300***	1.263***	2.555***	2.521***	2.425***
	V	V	0.674	0.675	0.676	1.327	1.326	1.324	2.583	2.581	2.572
	V	Λ	0.674	0.674	0.674	1.325	1.324	1.323	2.576	2.582	2.565**
	Λ	–	0.674	0.673	0.671***	1.324	1.323	1.319	2.572	2.573	2.567*
	Λ	/	0.679***	0.686***	0.703***	1.333***	1.351***	1.386***	2.599*	2.632***	2.716***
	Λ	\	0.669***	0.661***	0.639***	1.315***	1.296***	1.249***	2.549***	2.510***	2.408***
	Λ	V	0.674	0.674	0.672**	1.324	1.322	1.320	2.575	2.573	2.569.
	Λ	Λ	0.674	0.672*	0.668***	1.324	1.322	1.317*	2.578	2.565**	2.552***

From Table 6, one can conclude that the best MTPs differ between TR and ABL. In terms of TR, the best performing patterns are combinations of inverted bowl or descending configurations when applied to one of the parallel lines or both. Additionally, other good MT imbalance configurations are a balanced pattern in one parallel line, along with combinations of assorted patterns in the other parallel line, and a balanced pattern in both lines. Conversely, an ascending MTP in both parallel lines and an ascending or bowl patterns in one line with any other pattern in the other, all perform worse than the balanced line.

Table 4. TR data for an UR BC merging line with $N = 5$ and 8 parallel stations, BC = 2, 6 units, and 6 BCP; $p < .10$, *$p < .05$, **$p < .01$, ***$p < .001$.

Pattern		$N = 5$		$N = 8$	
L1	L2	BC = 2	BC = 6	BC = 2	BC = 6
–	–	0.559	0.657	0.509	0.625
–	/	0.561	0.658	0.509	0.615***
–	\	0.550***	0.645***	0.493***	0.597***
–	G1	0.558	0.656	0.506	0.621**
–	G2	0.558	0.655	0.505**	0.620**
–	Λ	0.560	0.658	0.508	0.621*
/	–	0.562	0.657	0.509	0.616***
/	/	0.562.	0.657	0.509	0.608***
/	\	0.553***	0.645***	0.495***	0.594***
/	G1	0.560	0.657	0.507	0.614***
/	G2	0.559	0.655	0.507	0.613***
/	Λ	0.563*	0.659	0.510	0.614***
\	–	0.551***	0.642***	0.493***	0.595***
\	/	0.552***	0.642***	0.493***	0.594***
\	\	0.542***	0.630***	0.478***	0.572***
\	G1	0.549***	0.641***	0.490***	0.593***
\	G2	0.549***	0.640***	0.489***	0.590***
\	Λ	0.552***	0.645***	0.492***	0.593***
G1	–	0.558	0.655	0.508	0.620**
G1	/	0.559	0.656	0.508	0.614***
G1	\	0.549***	0.643***	0.491***	0.593***
G1	G1	0.556	0.654	0.505**	0.617***
G1	G2	0.556	0.653*	0.504***	0.616***
G1	Λ	0.559	0.657	0.507	0.618***
G2	–	0.557	0.655	0.504***	0.618***
G2	/	0.559	0.653.	0.506	0.611***
G2	\	0.548***	0.641***	0.489***	0.590***
G2	G1	0.556	0.653.	0.502***	0.615***
G2	G2	0.554**	0.652**	0.502***	0.613***
G2	Λ	0.557	0.656	0.505**	0.616***
Λ	–	0.561	0.659	0.508	0.621
Λ	/	0.562	0.658	0.509	0.613***
Λ	\	0.553***	0.646***	0.492***	0.593***
Λ	G1	0.560	0.659	0.506.	0.617***
Λ	G2	0.558	0.657	0.505*	0.615***
Λ	Λ	0.562.	0.662***	0.507	0.619***

For ABL, best performance results are obtained from a descending pattern in one or both lines, which clearly outperform the ABL performance of a balanced control. Also seen is that an ascending MTP in one of the parallel lines together with any other pattern in the other line performs worse than the control.

Table 7 summarises the BCP results.

We can see that in Table 7 the best performing buffer allocation patterns regarding TR were found with an inverted bowl or an ascending pattern in one of the parallel lines, any other pattern in the other line; and a balanced line configuration.

Concerning ABL, best results for BCP were obtained from an ascending configuration in either line, which consistently outperforms both the balanced line and all other patterns for all factor levels considered. The worst ABL results are seen for a descending BCP in either parallel line, with the available BC concentrated towards the beginning of the line.

> Research Question 3: What are the relative contributions of MT imbalance pattern, imbalance degree, BC allocation pattern, line length and buffer capacity to line performance?

To determine the relative contributions of the independent variables on the dependent variables, a GLM analysis was carried out on the data. Tables 8 and 9 summarise the GLM results. Due to space constraints, only results for the highest significance levels (up to $p < .016$) are shown.

Table 5. ABL data for an UR merging line with $N = 5$ and 8 parallel stations, BC = 2, 6 units, and 6 BCP; $.p < .10$, $*p < .05$, $**p < .01$, $***p < .001$.

Pattern		$N = 5$		$N = 8$	
L1	L2	BC = 2	L1	L2	BC = 2
–	–	1.312	3.794	1.323	3.775
–	/	1.234***	3.512***	1.206***	3.327***
–	\	1.394***	4.079***	1.448***	4.254***
–	G1	1.330***	3.853***	1.350***	3.903***
–	G2	1.345***	3.903***	1.364***	3.950***
–	Λ	1.288***	3.706***	1.332***	3.841***
/	–	1.232***	3.511***	1.206***	3.322***
/	/	1.150***	3.227***	1.085***	2.912***
/	\	1.320***	3.817.	1.339***	3.871***
/	G1	1.249***	3.561***	1.237***	3.444***
/	G2	1.264***	3.613***	1.247***	3.504***
/	Λ	1.205***	3.405***	1.209***	3.374***
\	–	1.399***	4.108***	1.449***	4.278***
\	/	1.325***	3.850***	1.346***	3.894***
\	\	1.473***	4.356***	1.553***	4.600***
\	G1	1.413***	4.154***	1.475***	4.360***
\	G2	1.424***	4.196***	1.486***	4.406***
\	Λ	1.373***	4.019***	1.454***	4.322***
G1	–	1.332***	3.853***	1.353***	3.913***
G1	/	1.253***	3.576***	1.237***	3.464***
G1	\	1.412***	4.147***	1.475***	4.353***
G1	G1	1.346***	3.917***	1.380***	4.026***
G1	G2	1.359***	3.961***	1.393***	4.062***
G1	Λ	1.305**	3.750***	1.360***	3.950***
G2	–	1.345***	3.899***	1.367***	3.954***
G2	/	1.264***	3.623***	1.253***	3.517***
G2	\	1.422***	4.178***	1.484***	4.396***
G2	G1	1.361***	3.950***	1.391***	4.065***
G2	G2	1.374***	4.012***	1.406***	4.111***
G2	Λ	1.319**	3.819*	1.372***	4.005***
Λ	–	1.286***	3.687***	1.332***	3.842***
Λ	/	1.206***	3.412***	1.214***	3.393***
Λ	\	1.371***	4.009***	1.455***	4.307***
Λ	G1	1.303***	3.757***	1.359***	3.957***
Λ	G2	1.315	3.799	1.369***	4.005***
Λ	Λ	1.257***	3.598***	1.338***	3.881***

As seen in Table 8, all four main effects (N, BC, DI and MTP) are very highly significant at the $p < .001$ level for both TR and ABL regarding MTP experiments. The strongest effect on TR comes from BC, followed, respectively, by N, BC*N, DI, and MTP. For ABL, the most, very highly significant impact comes from BC. The next five contributions come from MTP, DI*MTP, BC*MTP, BC*DI*MTP and N.

Similarly, Table 9 shows that all three main effects (N, BC and BCP) are very highly significant for both TR and ABL regarding the BC merging line experiments and that the strongest effect on both TR and ABL comes from BC, followed by N, BC*N and BCP.

Research Question 4: Which pattern is the best in terms of combined TR and ABL performance?

As the MT and BC imbalance patterns giving the best performance differed between TR and ABL, it makes sense to determine an overall best pattern for combined TR and ABL performance.

To assess the impact of different MTPs and BCPs on the *Profit* function (the combined TR and ABL) performance, the value of h (the proportional inventory holding cost), where the *Profit* function that equates the pattern producing the maximum experimental TR ($\text{MTP}_{\text{maxTR}}$, $\text{BCP}_{\text{maxTR}}$) to the pattern resulting in the minimum experimental ABL ($\text{MTP}_{\text{minABL}}$, $\text{BCP}_{\text{minABL}}$) was calculated. For ease of reference, the best patterns for TR and ABL per system configuration are shown in the Appendix (Tables A4 and A5).

Table 6. Homogeneous subgroups for ranking of performance for different patterns of UR merging line MT imbalance.

Performance Indicator	Subgroup 1 (best patterns: L1, L2)	Subgroup 2 (medium patterns: L1, L2)	Subgroup 3 (worst patterns:L1, L2)
TR	Λ, Λ	Λ, V	–, /
	\, Λ	–, V	Λ, /
	Λ, –	\, V	\, /
	–, Λ	V, Λ	/, –
	Λ, \	V, \	/, Λ
	\, –	V, –	/, \
	\, \	V, V	V, /
	–, –		/, V
	–, \		/, /
ABL	\, \	Λ, Λ	V, /
	\, Λ	Λ, V	Λ, /
	Λ, \	Λ, –	–, /
	\, –	\, /	/, V
	\, V	V, V	/, Λ
	–, \	–, V	/, –
	V, \	–, Λ	/, /
		–, –	
		V, Λ	
		V, –	
		/, \	

Table 7. Homogeneous subgroups for ranking of performance for different patterns of UR merging line buffer imbalance.

Performance indicator	Subgroup 1 (best patterns: L1, L2)	Subgroup 2 (medium patterns: L1, L2)	Subgroup 3 (worst patterns:L1, L2)
TR	Λ, –	Λ, G2	/, \
	Λ, Λ	/, G2	–, \
	–, –	G2, Λ	Λ, \
	–, Λ	G2, –	\, Λ
	/, Λ	G1, G1	\, –
	–, /	G2, /	\, /
	/, –	G1, G2	G1, \
	Λ, /	G2, G1	\, G1
	Λ, G1	G2, G2	G2, \
	G1, Λ		\, G2
	–, G1		\, \
	G1, –		
	/, G1		
	–, G2		
	G1, /		
	/, /		
ABL	/, /	–, –	Λ, \
	/, Λ	/, \	\, Λ
	Λ, /	G1, Λ	–, \
	/, –	Λ, G1	\, –
	–, /	\, /	G1, \
	/, G1	–, G1	\, G1
	G1, /	G1, –	G2, \
	/, G2	Λ, G2	\, G2
	G2, /	G2, Λ	\, \
	Λ, Λ	–, G2	
	Λ, –	G2, –	
	–, Λ	G1, G1	
		G2, G1	
		G1, G2	
		G2, G2	

Table 8. GLM results for TR and ABL regarding the MT merging line set of experiments.

Throughput (TR)			ABL		
Source (Factor)	*F*-value	Significance level	Source (Factor)	*F*-value	Significance level
BC	446,900.00	0.000***	BC	9,056,000.00	0.000***
N	146,700.00	0.000***	*MTP*	3984.00	0.000***
BC**N*	3603.00	0.000***	DI**MTP*	2429.00	0.000***
DI	1149.00	0.000***	BC**MTP*	1378.00	0.000***
MTP	201.80	0.000***	BC*DI**MTP*	847.1	0.000***
DI**MTP*	87.10	0.000***	*N*	359.20	0.000***
BC*DI	27.11	0.000***	*N***MTP*	39.75	0.000***
*N***MTP*	22.04	0.000***	BC**N*	33.72	0.000***
*N**DI	15.91	0.000***	DI	27.35	0.000***
*N**DI**MTP*	10.23	0.000***	*N**DI**MTP*	22.19	0.000***
BC**MTP*	6.10	0.000***	BC*DI	15.05	0.000***
			BC**N***MTP*	7.42	0.000***
			BC**N**DI**MTP*	3.46	0.016*

Significant at $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Table 9. GLM results for TR and ABL regarding the BC merging line set of experiments.

	Throughput (TR)		ABL	
Source (Factor)	*F*-value	Significance level	*F*-value	Significance level
BC	413,000.0	0.000***	689,078.9	0.000***
N	95,070.0	0.000***	14,859.3	0.000***
BC**N*	1690.0	0.000***	3619.7	0.000***
BCP	510.2	0.000***	2301.6	0.000***
BC**BCP*	35.3	0.000***	631.2	0.000***
*N***BCP*	43.5	0.000***	782.6	0.000***
BC**N***BCP*	5.6	0.000***	190.8	0.000***

Significant at $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Assuming that the *Profit* is equal between $\mathrm{MTP}_{\mathrm{maxTR}}$ and $\mathrm{MTP}_{\mathrm{minABL}}$, the value of h was calculated from the following equation:

$$\mathrm{TR}_{\mathrm{MTPmaxTR}} - \mathrm{hABL}_{\mathrm{MTPmaxTR}} = \mathrm{TR}_{\mathrm{MTPminABL}} - \mathrm{hABL}_{\mathrm{MTPminABL}} \tag{3}$$

where $\mathrm{TR}_{\mathrm{MTPmaxTR}}$ and $\mathrm{ABL}_{\mathrm{MTPmaxTR}}$ are, respectively, the TR and ABL resulting from the MTP with the maximum experimental TR; and $\mathrm{TR}_{\mathrm{MTPminABL}}$ and $\mathrm{ABL}_{\mathrm{MTPminABL}}$ are, respectively, the TR and ABL resulting from the MTP with the minimum experimental ABL.

Therefore,

$$h_0 = \frac{TR_{MTP_{maxTR}} - TR_{MTP_{minABL}}}{ABL_{MTP_{maxTR}} - ABL_{MTP_{minABL}}} \tag{4}$$

where h_0 is the value of h in the *equilibrium point.*

The h_0 value can be used as a yardstick for deciding the best performing pattern regarding the profit function, depending on the actual value of h for a particular manufacturing firm. For instance, in manufacturing firms with higher values of h than h_0, $\mathrm{MTP}_{\mathrm{minABL}}$ will result in the best *Profit*, since reducing ABL will carry more importance (weight) than increasing TR, as the inventory holding costs are high in comparison with the total TR generated. On the contrary, manufacturing firms with lower values of h than h_0 will have a higher *Profit* with $\mathrm{MTP}_{\mathrm{maxTR}}$, as inventory holding costs are not as critical, and so an MTP that increases TR will result in the best-combined performance.

Figure 2 shows the values of h_0, based on MTP experimental results of the present study. For instance, the line representing UR with $N = 5$ (blue line with round dots) in Figure 2 shows that when $\mathrm{BC} = 1$ and $\mathrm{DI} = 5$, $h_0 = 0.039$, meaning that an

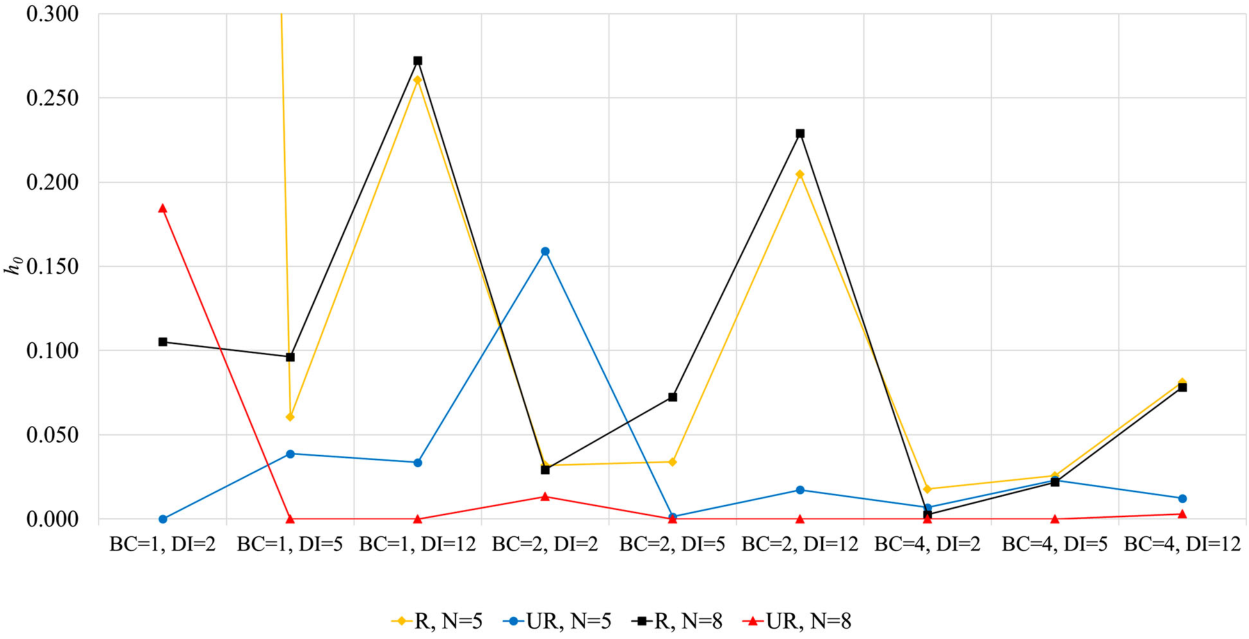

Figure 2. Values of h_0 for the MTP set of experiments, according to reliability, N, BC and DI values.

UR merging line with $h < 0.039$ will have a higher *Profit* with the $\text{MTP}_{\text{maxTR}}$, i.e. (Λ, \), than with the $\text{MTP}_{\text{minABL}}$, i.e. (\, \). However, UR merging lines with $h > 0.039$, BC = 1, DI = 5 and $N = 5$ will have a higher *Profit* with the (\, \) pattern than the (Λ, \) pattern as the (\, \) pattern is the best MTP for reducing the inventory holding costs. The profit function is equal between the patterns (\, \) and (Λ, \) when $h = 0.039$, in this case.

From Figure 2, it can be observed that as UR merging lines had generally more ABL than reliable (R) lines (McNamara et al. 2018; Shaaban, McNamara, and Dmitriev 2017), they are more highly penalised by increasing inventory holding costs (h) values, because even small h values will mean that $\text{MTP}_{\text{minABL}}$ is more profit-effective than $\text{MTP}_{\text{maxTR}}$.

Furthermore, the value of h_0 in reliable lines increases with higher DI values and lower BC values due to the resulting lower ABL produced by the $\text{MTP}_{\text{minABL}}$ in high DIs and low BCs. Lower ABL, in turn, results in lower inventory holding cost penalties for the profit function and a higher relevance of $\text{MTP}_{\text{maxTR}}$.

A special case can be found in the reliable scenario, where $N = 5$, BC = 1 and DI = 2, because h_0 is equal to 3.5! This result shows that the overall cost of ABL is very low in this scenario to have an impact on the total profit function.

Figure 3 shows the h_0 values for BCP experiments.

Similar to Figure 2's results, those of Figure 3 suggest that UR lines are significantly more penalised by inventory holding costs than R lines because they tend to carry more ABL values than R lines, due to inefficiency caused by unreliability. Because of this particular issue, h_0 values for BCP experiments are much lower for UR lines than for R lines.

Moreover, lower BC values for reliable lines and BCP experiments continue to produce higher h_0 values, similar to the results from MTP experiments. However, the opposite behaviour is seen in h_0 values for UR lines regarding BCP merging line experiments, as higher BC values result in higher h_0 values. This particular behaviour might be caused by the effect of higher BC on producing higher TR. Thus, even though a higher BC will also result in higher ABL, the effect of BC on TR can offset the inventory holding costs of ABL for UR lines, producing a higher h_0 value for these configurations.

Research Question 5: What is the effect of unreliability on the performance of unbalanced MT and BC merging lines?

McNamara et al. (2018) stated that for reliable, MT unbalanced merging lines, improved TR and ABL performance were obtained for a balanced line arrangement and a monotone decreasing order, respectively. For UR merging lines, a similar result was obtained for ABL.

However, for TR the best patterns turned out to be combinations of the inverted bowl or descending orders, but none was significantly different from a corresponding balanced merging line regarding MTP. Therefore, it only makes sense to

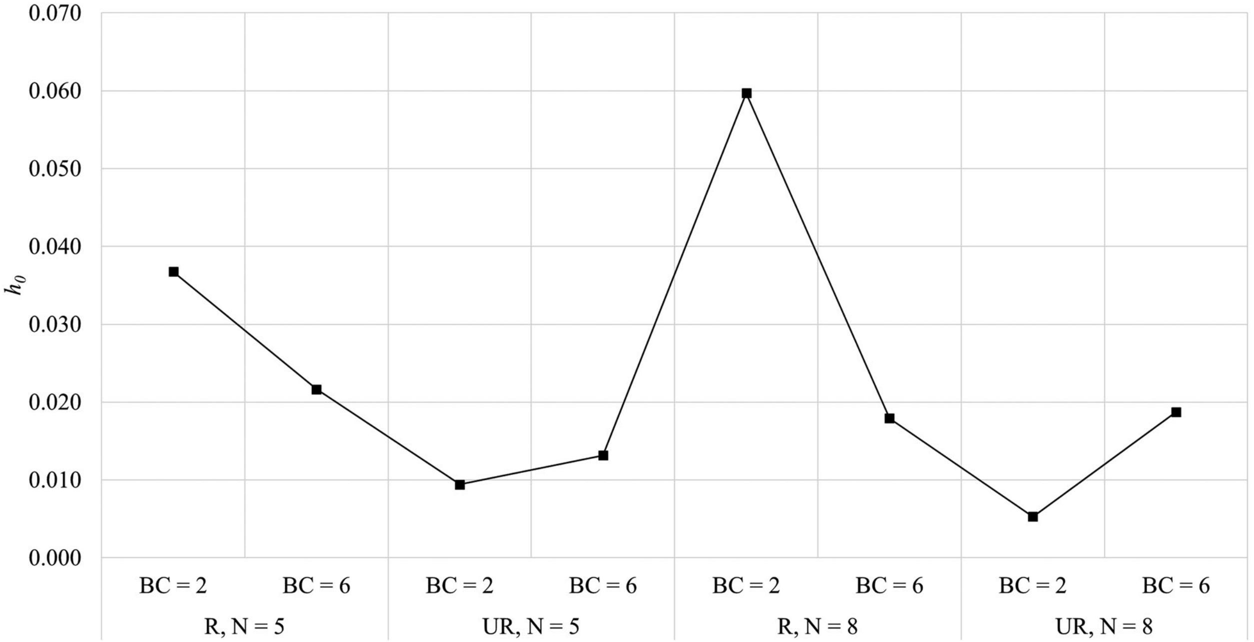

Figure 3. Value of h_0 for the BCP set of experiments, according to reliability, N and BC values.

compare the percentage improvements in ABL for the best pattern for reliable and UR merging lines. Table 10 displays the comparison.

It is to be expected that lines suffering from breakdown will perform less well than their reliable counterparts, since we are adding even more fluctuation into the line. When the results in Table 10 are examined, it can be noted that in all instances, the reliable line gave higher savings in ABL over the balanced line, as compared to the UR line for all the N, BC and DI% levels considered.

On the other hand, when compared with previous results regarding buffer allocation patterns (Shaaban, McNamara, and Dmitriev 2017), results from BCP experiments (see Table 11) suggest that UR lines can be more sensitive to changes in buffer allocation patterns than reliable lines, improving TR performance with an inverted bowl pattern (Λ, Λ) when $N=5$, or with a (/, Λ) pattern when $N=8$ and BC = 2.

Big differences between R and UR merging lines were also found regarding the impact of inventory holding costs on the profit function, because even with very low values of h, the patterns generating the highest profit in UR merging lines are those that reduce ABL, rather than those that increased TR.

Figures comparing R and UR lines in terms of TR and ABL can be found in the supplementary material of the paper (see Appendix).

Table 10. Percentage savings in ABL for their best MTP (\, \), compared to the equivalent balanced merging line.

		$N=5$		$N=8$	
BC	% DI	Reliable	UR	Reliable	UR
1	2	−4.88	−2.07	−8.77	−1.52
	5	−16.67	−5.29	−25.33	−4.00
	12	−35.52	−13.28	−37.09	−10.47
2	2	−11.52	−1.97	−0.35	−1.50
	5	−20.00	−5.38	−14.16	−4.21
	12	−30.09	−13.97	−28.76	−10.88
4	2	−22.59	−2.46	−13.58	−2.19
	5	−32.66	−6.12	−36.47	−5.18
	12	−34.89	−15.71	−50.98	−13.29

Table 11. Percentage improvements in TR for their best BCP, compared to the equivalent balanced merging line.

Pattern L1, L2	BC	*N* = 5 Reliable	UR	*N* = 8 Reliable	UR
(Λ, Λ)	2	−1.69	0.63	−2.77	−0.38
	6	−1.12	0.78	−0.82	−0.89
(/, Λ)	2	−1.91	0.71	−2.35	0.16
	6	−1.23	0.36	−0.72	−1.64

6. Summary and discussion of results

When considering TR, an inverted bowl (Λ) or a descending (\) MTP in either L1 or L2 generate superior performance. This partially agrees with Magazine and Stecke (1996) suggestion that the symmetrical allocation property holds in that more work should be assigned to the middle station. However, it does not concur with the finding of McNamara et al. (2018) for reliable merging lines that the balanced line arrangement for both parallel lines (–, –) was generally the best. Nevertheless, the current study indicates that this pattern is actually a good one. Our results also show that there is no significant difference in TR between the best and other good MT unbalanced configurations, and the balanced line counterpart.

In addition, inverted bowl (Λ), ascending (/) or balanced BCP in either L1 or L2 result in good TR performance, somewhat contrasting with previous single (Lambrecht and Segaert 1990) and merging line research (Shaaban, McNamara, and Dmitriev 2017) which suggest that the balanced BCP results in the best TR performance.

With respect to ABL, the MTP generating the lowest (best) ABL performance, was found to be a descending MT order in both lines (\, \). This agrees with McNamara et al. (2018) finding for reliable, MT unbalanced merging lines, and also with Kadipasaoglu et al.'s (2000) conclusion for single lines in series, which places the constraint station at the first location to generate the lowest amount of WIP. It was also seen that the ascending BCP in both lines (/, /) produce the best ABL results for all configurations, which is in line with previous findings (Shaaban, McNamara, and Dmitriev 2017).

For the MT UR merging line investigation, it was seen that many descending patterns resulted in substantial ABL performance improvements over the control, while most ascending patterns resulted in substandard performance. For the best ABL pattern (\, \), consistent, mostly highly significant improvements over the balanced line are obtained for all the *N*, BC and DI values experimented with.

In terms of overall savings, the greatest % TR improvements over the balanced line counterpart is 0.52% (not statistically significant), which was obtained for the descending MTP in L1 and the balanced pattern in L2 (\, –) (at *N* = 5, BC= 2 and DI = 5%).

In contrast, the highest % ABL saving over an equivalent balanced merging line configuration is about 15.71% (very highly significant), which was achieved for the descending pattern in both parallel lines (\, \) (at *N* = 5, BC = 4 and %DI = 12%).

Moreover, it was noted that for all the factor levels considered, a reliable line generates higher ABL savings over a balanced line, as compared to a corresponding UR line.

When considering the combined performance of TR and ABL, the analysis of merging lines with *N* = 8 is easy to carry out, as the descending MTP for both lines (\, \) performed well for both TR and ABL (see Table A4 in the Appendix). However, when considering merging lines with *N* = 5, the best MTP regarding the profit function is not as clear, because it depends on the value of inventory holding costs. Thus, with higher inventory holding costs, the descending MTP for both lines (\, \) will be the best in terms of profit but with lower inventory costs, different patterns will produce the best profit.

For the BCP UR merging line investigation, the best results in terms of TR were obtained from the inverted bowl configuration in both parallel lines (Λ, Λ) for *N* = 5 and a combination of ascending pattern in L1 and inverted bowl in L2 (/, Λ) for *N* = 8. This conclusion is not in line with the finding of Shaaban, McNamara, and Dmitriev (2017), who reported that for reliable merging lines the balanced arrangement in both parallel lines (–, –) was generally superior.

In terms of ABL, it was found that the best uneven buffer allocation pattern is an ascending pattern for both parallel lines (/, /), i.e. concentrating BC towards the end of the line. This agrees with Shaaban, McNamara, and Dmitriev (2017) finding for asymmetric BC reliable merging lines.

With respect to overall performance, the highest %TR improvement over the balanced line counterpart is 0.78% (very highly significant), obtained for the inverted bowl BCP in both L1 and L2 (Λ, Λ), with a TR of 0.662 (at *N* = 5, BC = 6), compared to 0.657 for the balanced control, as shown in Table 11.

In contrast, the greatest percentage of ABL edge over an equivalent balanced merging line is 22.87% (very highly significant), achieved for the ascending BCP in both L1 and L2 (/,/), with an ABL of 2.912 (at $N = 8$ and BC = 6), in comparison with 3.776 for the balanced line.

Furthermore, it was found that the overall best pattern for combined TR and ABL is highly dependent on the unitary inventory holding costs as the ascending BCP in both lines (/, /) will result in the best profit with higher costs, but when holding costs are lower, various different patterns will produce the best profit, depending on the N and BC values.

Results regarding TR and ABL are both in line with the findings of Hillier (2013), who suggested that when considering a profit function with high inventory holding costs for single serial lines, the best combination of MTP and BCP was a descending MTP and an ascending BCP.

Moreover, because of the resulting higher ABL values on UR lines, it was found that UR lines are highly penalised in their profits by even the lowest inventory holding cost values when compared with reliable lines. Consequently, the profit performance in UR lines is more dependent on controlling inventory holding costs through a good allocation of work and buffer than the performance of reliable lines. The profit function of reliable lines, on the other hand, tends to increase by using a TR-maximising pattern, even in high inventory holding costs environments, i.e. $h > 0.2$ (Azzi et al. 2014), where the percentage degree of imbalance is 12%. Thus, the best pattern for a combined performance of TR and ABL is highly dependent on the value of h.

It was also found that all the main design factors, i.e. BCP, MTP, DI, BC and N have very highly significant effects on TR and ABL performance.

Finally, the following general conclusions, also found in previous single line studies (Conway et al. 1988; Tan 1998; Kalir and Sarin 2009; Hillier and So 1991), were discerned from the overall results (both MTP and BCP experiments):

- Increasing N generally lowers TR performance.
- As BC goes up, both TR and ABL tend to increase.
- No clear relationship was found between DI and TR and ABL.
- Unreliability significantly affects the performance of both TR and ABL.

7. Conclusions and future research directions

Contributing to the body of knowledge of production lines, this study provides new insights into how to improve performance in MT and BC unbalanced, UR merging assembly lines; applicable to reverse logistics, developing economies and remanufacturing.

Substantial capital and other resources are invested by companies on the design, installation, operation and maintenance of merging assembly lines. Even slight throughput improvements or inventory cost reductions can result in substantial savings over a merging line's lifetime.

An MT balanced merging line is unlikely to be achieved in practice, particularly in the global context of outsourcing to developing countries, where low-cost, perhaps untrained, operators recruited on an ad hoc project basis, may not have the time, motivation, or expertise for consistent performance.

Study results indicate that statistically equivalent TR performance to that of a balanced merging line can be obtained in many MT configurations. Conversely, highly significant ABL savings are attainable in many MT and BC patterns (more than 15% for the best case). Such savings, when multiplied over the lifespan of a production line, indicate that it could be worthwhile to deliberately unbalance UR merging lines in many situations, especially as the improvements in ABL only require to appropriately reassign line operators, entailing no further capital or resource expenditures. Furthermore, specific unbalanced BC allocation policies resulted in higher statistically significant TR values.

However, a line manager will need to make decisions regarding where the greatest benefits can be gained. In an industry with high demand and fully utilised, expensive operators (e.g. the IT and pharmaceutical industries), TR may be prioritised. In these cases, the best choice of MT and BC patterns will depend on the specific line characteristics, i.e. its reliability, number of buffers and number of stations.

In a just-in-time industry which emphasises lean buffering (e.g. the automotive or electronics industries) and where inventory holding costs are high, ABL should be prioritised. In this case, a combination of a descending MT pattern (fastest operators at the end) with an ascending BC pattern (biggest BC at the end) would be the most appropriate.

On the other hand, if a manager wants to consider combined overall TR and ABL performance, the best pattern will be highly dependent on the relative inventory holding costs and on the specific characteristics of the merging line.

Despite its contribution to production line research, this study has limited generalisability. Simulation is a valuable analytical tool that can represent realistic situations more accurately than many mathematical models, yet generalising complex system results is an exercise to be approached with caution. Results here are based on a series of simulation experiments on only a limited number of MT and BC unbalanced configurations amongst an almost infinite number of alternatives, as well as on theoretical probability distributions, instead of being based on a real industrial setting. It should also be noted that the results reported here are only valid for the particular line type and parameter values used.

Nevertheless, simulation allows us to generate a number of alternatives to aid decision-making, while avoiding the lengthy and case-specific nature of field observation. Therefore, despite the potential benefits of an unbalanced, UR merging line, if the line was imbalanced inappropriately, adverse performance could result.

A considerable amount of possible research based on this study can still be done. Future research could explore UR merging assembly lines with unequal variability. Another research possibility is to study the UR, unbalanced disassembly lines that are common in reverse logistics and remanufacturing industries. More research is also needed to study the performance of real manufacturing scenarios in the presence of MT and BC imbalance patterns.

Finally, as this study has only considered a constant and balanced unreliability efficiency rate along the line, future research can investigate the effect of an unbalanced unreliability on performance and how different mixtures of mean time to failure and repair can affect the performance of various MT and BC imbalance patterns.

Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed https://doi.org/10.1080/00207543.2018.1495344

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Appendix

Table A1. Weibull parameters of Location (α) and Range (λ) per station, depending on MTP for $N = 5$, with Shape parameter $k = 1.6$, where α_i is the location parameter of the ith station in both L1 and L2 (S_{i1} and S_{i2}, respectively) and λ_i is the range parameter of the ith station in both L1 and L2.

DI	MTP	α_1	α_2	α_3	α_4	α_5	λ_1	λ_2	λ_3	λ_4	λ_5
0	–	5.780	5.780	5.780	5.780	5.780	4.702	4.702	4.702	4.702	4.702
2	/	5.664	5.722	5.780	5.838	5.896	4.608	4.655	4.702	4.749	4.796
2	\	5.896	5.838	5.780	5.722	5.664	4.796	4.749	4.702	4.655	4.608
2	Λ	5.722	5.780	5.838	5.780	5.722	4.655	4.702	4.749	4.702	4.655
2	V	5.838	5.780	5.722	5.780	5.838	4.749	4.702	4.655	4.702	4.749
5	/	5.474	5.627	5.780	5.933	6.086	4.453	4.577	4.702	4.827	4.951
5	\	6.086	5.933	5.780	5.627	5.474	4.951	4.827	4.702	4.577	4.453
5	Λ	5.630	5.780	5.930	5.780	5.630	4.580	4.702	4.824	4.702	4.580
5	V	5.930	5.780	5.630	5.780	5.930	4.824	4.702	4.580	4.702	4.824
12	/	4.994	5.387	5.780	6.173	6.566	4.063	4.382	4.702	5.022	5.342
12	\	6.566	6.173	5.780	5.387	4.994	5.342	5.022	4.702	4.382	4.063
12	Λ	5.387	5.780	6.173	5.780	5.387	4.382	4.702	5.022	4.702	4.382
12	V	6.173	5.780	5.387	5.780	6.173	5.022	4.702	4.382	4.702	5.022

Table A2. Weibull parameters of Location (α) and Range (λ) per station, depending on MTP for $N = 8$, with Shape parameter $k = 1.6$, where α_i is the location parameter of the ith station in both L1 and L2 (S_{i1} and S_{i2}, respectively) and λ_i is the range parameter of the ith station in both L1 and L2.

DI	MTP	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8
0	–	5.78	5.78	5.78	5.78	5.78	5.78	5.78	5.78	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70
2	/	5.66	5.70	5.73	5.76	5.80	5.83	5.86	5.90	4.61	4.63	4.66	4.69	4.72	4.74	4.77	4.80
2	\	5.90	5.86	5.83	5.80	5.76	5.73	5.70	5.66	4.80	4.77	4.74	4.72	4.69	4.66	4.63	4.61
2	V	5.84	5.80	5.77	5.74	5.74	5.77	5.80	5.84	4.75	4.72	4.70	4.67	4.67	4.70	4.72	4.75
2	Λ	5.74	5.77	5.80	5.84	5.84	5.80	5.77	5.74	4.67	4.70	4.72	4.75	4.75	4.72	4.70	4.67
5	/	5.47	5.56	5.65	5.74	5.82	5.91	6.00	6.09	4.45	4.52	4.60	4.67	4.74	4.81	4.88	4.95
5	\	6.09	6.00	5.91	5.82	5.74	5.65	5.56	5.47	4.95	4.88	4.81	4.74	4.67	4.60	4.52	4.45
5	V	5.93	5.84	5.76	5.67	5.67	5.76	5.84	5.93	4.82	4.75	4.68	4.61	4.61	4.68	4.75	4.82
5	Λ	5.67	5.76	5.84	5.93	5.93	5.84	5.76	5.67	4.61	4.68	4.75	4.82	4.82	4.75	4.68	4.61
12	/	4.99	5.22	5.44	5.67	5.89	6.12	6.34	6.57	4.06	4.25	4.43	4.61	4.79	4.98	5.16	5.34
12	\	6.57	6.34	6.12	5.89	5.67	5.44	5.22	4.99	5.34	5.16	4.98	4.79	4.61	4.43	4.25	4.06
12	V	6.17	5.95	5.72	5.50	5.50	5.72	5.95	6.17	5.02	4.84	4.66	4.47	4.47	4.66	4.84	5.02
12	Λ	5.50	5.72	5.95	6.17	6.17	5.95	5.72	5.50	4.47	4.66	4.84	5.02	5.02	4.84	4.66	4.47

Table A3. Buffer capacity distribution per station, depending on BCP.

Line length (N)	5		8	
Mean buffer capacity (BC)	2	6	2	6
–	2,2,2,2	6,6,6,6	2,2,2,2,2,2,2	6,6,6,6,6,6,6
/	1,1,1,5	3,3,3,15	1,1,1,1,1,1,8	3,3,3,3,3,3,24
\	5,1,1,1	15,3,3,3	8,1,1,1,1,1,1	24,3,3,3,3,3,3
G1	2,2,3,1	6,6,9,3	2,2,2,3,3,1,1	6,6,6,9,9,3,3
G2	2,3,2,1	6,9,6,3	2,2,3,3,2,1,1	6,6,9,9,6,3,3
Λ	1,2,3,2	3,6,9,6	1,1,3,4,3,1,1	3,3,9,12,9,3,3

Table A4. Best MTP for TR and ABL in each experimental scenario for reliable and unreliable lines.

	R, $N = 5$*		UR, $N = 5$		R, $N = 8$*		UR, $N = 8$	
BC, DI	TR	ABL	TR	ABL	TR	ABL	TR	ABL
BC = 1, DI = 2	\, Λ	\, –	\, \	\, \	\, –	\, \	\, –	\, \
BC = 1, DI = 5	–, –	\, \	Λ, \	\, \	–, V	\, \	\, \	\, \
BC = 1, DI = 12	–, –	\, \	Λ, Λ	\, \	–, –	\, \	\, \	\, \
BC = 2, DI = 2	–, Λ	\, \	\, V	\, \	V, –	\, –	–, –	\, \
BC = 2, DI = 5	–, Λ	\, \	\, –	\, \	–, –	\, Λ	\, \	\, \
BC = 2, DI = 12	–, –	\, \	Λ, Λ	\, \	–, –	\, \	\, \	\, \
BC = 4, DI = 2	–, Λ	\, \	\, Λ	\, \	/, –	\, \	\, \	\, \
BC = 4, DI = 5	–, –	\, \	\, Λ	\, \	–, –	\, \	\, \	\, \
BC = 4, DI = 12	–, –	/, \	–, Λ	\, \	–, –	\, \	–, \	\, \

*Results from previous studies.

Table A5. Best BCP for TR and ABL in each experimental scenario for reliable and UR lines.

	R, $N = 5$*		UR, $N = 5$		R, $N = 8$*		UR, $N = 8$	
BC	TR	ABL	TR	ABL	TR	ABL	TR	ABL
BC = 2	–, –	/, /	/, Λ	/, /	–, –	/, /	/, Λ	/, /
BC = 6	–, G2	/, /	Λ, Λ	/, /	–, –	/, /	–, –	/, /

*Results from previous studies

Supplementary material (Figures comparing R and UR lines) can be found at:
https://drive.google.com/file/d/1aI3HSjBCqDBboMFiBafh3HXhqMF8fQJ9/view?usp=sharing